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Evaluation of PAT Performances by Modified Affinity Law.

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Abstract

The use of pumps operating as a turbines (PATs) is an alternative cheap solution for the conversion of dissipations along the distribution networks, but a little information about their performance is available.
The turbomachinery affinity law can be applied for the evaluation of the performances curves, but can produce relevant errors that can be reduced with a modification of the affinity law. This research, which is based on experimental collected data, proposes a modification of the turbomachinery affinity law in order to minimize the differences between experimental data and the predicted curves.

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Keywords: Pump as Turbine (PAT); Variable Operating Strategy (VOS); Turbomachinery affinity law; Suter parameters

1. Introduction

Pump operating as turbine (PAT) can be used in alternative of traditional turbines, to reduce the equipment cost of small hydropower plants [1, 2]. Unfortunately, the lack of information on the PATs performances represents a limit for their wider diffusion. Furthermore, a large variability of operating condition is present for the exploitation of hydraulic power within water distribution networks and a full set of characteristic curves of several different PATs rotating at different speeds is needed for power plant design. In order to face with the hydraulic variability, a new procedure, namely VOS (Variable Operating Strategy), was proposed, based on either a hydraulic or an electric regulation of the PAT [3, 4]. The hydraulic regulation system consists in a series-parallel circuit with a PAT and two

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regulating valves, while for the electric regulation the PAT generator is connected to an inverter which modifies the rotational speed of the machine.

PAT performances are described by both the characteristic and the efficiency curves, that can be obtained in three ways: experimentally [5, 6], by computational fluid dynamics (CFD) [7, 8] and by any one-dimensional method [6, 9]. The device efficiency curve, depending on the discharge, presents a maximum: the corresponding values of discharge head drop and efficiency (Q_B, H_B, η_B) are called Best Efficiency Point (BEP). Unfortunately, producers usually do not provide the performances curves of pump working in inverse mode and the lack of data constitutes an obstacle to the choice of a PAT instead of a traditional turbine.

Once the characteristic and efficiency curves of a single prototype are available, the results may be extended to obtain the characteristic curves of other mechanically similar devices. The turbomachinery affinity law predicts the BEP of the new machines with different diameters and operating speed, and then also the machine performance curves can be evaluated. The procedure of using the affinity law and the Suter parameters [10, 11] can be very useful in the design of the energy recovery system [12, 13], but can produce large errors [14].

In this paper the results of the affinity law modeling are compared with a large dataset of experimental characteristic curves, obtained for several submersible semi-axial single stage pumps, operating at different rotating speed. Then an alternative modeling is proposed in order to reduce the scatters between theoretical and experimental performance curves.

2. PAT characteristic curves and affinity law

PAT characteristic curves can be obtained in three ways: experimentally [6, 15, 16], by computational fluid dynamics (CFD) [7, 17, 18] and by any one-dimensional method [19, 20, 21, 22, 23, 24, 25].

According to Fig. 1, once a single PAT characteristic curve is available, the best efficiency points of the pump working with different rotational speeds can be determined by turbomachinery affinity law:

$$\frac{N_B^I}{N_B^{II}} = \frac{D^{II}}{D^I}\left(\frac{H_B^I}{H_B^{II}}\right)^{\frac{1}{2}} = \left(\frac{Q_B^I}{Q_B^{II}}\right)^{\frac{1}{2}}\left(\frac{H_B^I}{H_B^{II}}\right)^{\frac{3}{4}} = \left(\frac{P_B^I}{P_B^{II}}\right)^{\frac{1}{2}}\left(\frac{H_B^I}{H_B^{II}}\right)^{\frac{5}{4}} \tag{1}$$

being N and D, rotational speed, impeller diameter, Q and H, flow rate and head drop, P the produced power, and using the superscript I and II for the prototype and for a different similar machine, respectively. It is important to underline that, according to Eq. (1), η_B is constant for all similar machines and does not depend on either the diameter or the rotating speed.

Then, the whole characteristic and efficiency curves, respectively H=H(Q) and η=η(Q), can be calculated by the application of Suter model, by defining the two parameters:

$$WH = \frac{h}{q^2\left(\theta^2+1\right)}; \qquad WT = \frac{t}{q^2\left(\theta^2+1\right)} \tag{2}$$

With

$$\theta = \frac{\omega}{q};\ h = \frac{H}{H_B};\ \omega = \frac{N}{N_B};\ q = \frac{Q}{Q_B};\ t = \frac{T}{T_B}$$

where t is the torque and is equal to the ratio between the power and the rotational speed. The two functions $WH(\theta)$ and $WT(\theta)$ are unique for similar machines. Thus, once they are deduced for the prototype, the head drop $H(Q)$ and the efficiency $\eta(Q)$ of similar PAT, operating in the condition defined by θ, can be calculated [12]:

$$H = \left[q^2 \left(\theta^2 + 1 \right) WH \right] H_B; \ \eta = \theta \frac{WT}{WH} \eta_B \tag{3}$$

In Fig. 1 The characteristic curves of a machine are showed as an example.

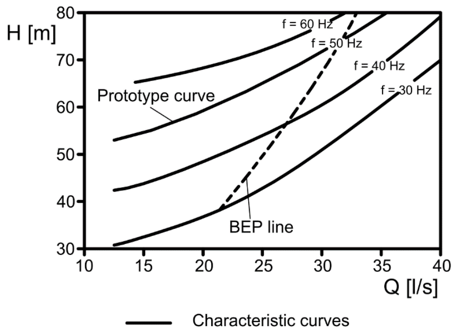

Fig. 1. Envelope of characteristic curves for similar turbomachinery.

3. Data set

An experimental data set relative to the behavior of 5 semiaxial, submersible and single stage pumps operating as turbines is available to the authors. For each PAT both the characteristic and the efficiency curves have been measured for rotational velocities varying between 750 and 1860 rpm. A total of 87 operating points have been measured to obtain 20 different curves.

In order to find the agreement between real (experimental) and calculated (affinity law and Suter parameters) $H(Q)$ and $\eta(Q)$ curves, each experimental curve of each PAT has been used as prototype curve. Then the performances curves has been extended to the other velocity values of the dataset and $H(Q)$ and $\eta(Q)$ values have been compared. For each couple of characteristic curves, the error σ^H , which accounts the discrepancies between the calculations and experiments, has been expressed by:

$$\sigma^H = \frac{1}{m} \sqrt{\sum_{i=1}^{n} \left(\frac{H_i^{exp} - H_i^{calc}}{H_i^{exp}} \right)^2} \tag{4}$$

while, for the efficiency curves, the error σ^η:

$$\sigma^\eta = \frac{1}{m} \sqrt{\sum_{i=1}^{n} \left(\frac{\eta_i^{exp} - \eta_i^{calc}}{\eta_i^{exp}} \right)^2} \tag{5}$$

where m is the number of experimental measurements for each curve, the superscripts “exp” and “calc” refer to the experimental and calculated values of the related variable respectively.

The resulting values of σ^H and σ^η are plotted in Fig. 2 versus n, where $n = (N^{exp} - N^{calc})/N^{exp}$, N^{exp} is the rotational velocity of the prototype curves and N^{calc} the rotational velocity of the calculated curves. It is clear that n could assume both positive (+) and negative (−) values, depending on the respective velocities of prototype and simulated machine.

From the application of affinity law and Suter parameters, the largest error values were observed for the highest differences in rotational speed [14]. Average values of σ_H and σ_η are equal to 0.0991 and 0.1536, respectively.

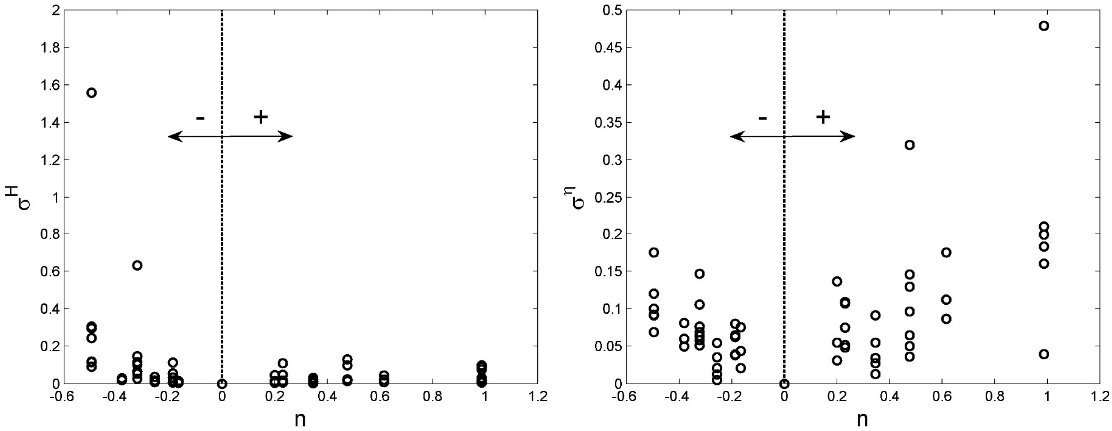

Fig. 2. Values of errors in the evaluation of head drop and efficiency according to Eqq. (4) and (5) versus n.

4. Modified affinity law

The comparison between experimental and calculated affinity law suggests that an improvement in the prediction of PAT characteristic curve could be obtained by a modification of the affinity law, i.e. by relaxing the connection between working parameters given by Eq. 1.

In terms of machine efficiency it is clear that the maximum efficiency is not constant with the rotational speed as stated by the affinity law. Instead, efficiency at BEP attains its maximum value η_B^{max} for a speed N^{max}, different for each PAT.

Therefore, it was assumed that the position of the BEP at a certain value of speed (N^{II}) it is an unknown function of the ratio (N^{II}/N^{max}). According to this position affinity laws were modified as follows:

$$q = \frac{Q_B^{II}}{Q_B^{\max}} = f_1\left(\frac{N^{II}}{N^{\max}}\right) \tag{6}$$

$$h = \frac{H_B^{II}}{H_B^{\max}} = f_2\left(\frac{N^{II}}{N^{\max}}\right) \tag{7}$$

$$p = \frac{P_B^{II}}{P_B^{\max}} = f_3\left(\frac{N^{II}}{N^{\max}}\right) \tag{8}$$

$$\varepsilon = \frac{\eta_B^{II}}{\eta_B^{\max}} = f_1\left(\frac{N^{II}}{N^{\max}}\right) \tag{9}$$

where Q_B^{max}, H_B^{max}, P_B^{max} and η_B^{max} are the discharge, the head, the produced power and the efficiency at BEP for a rotating speed equal to N^{max}.

Test results were used to obtain by best fit a polynomial expression of the functions f_1, f_2, f_3 and f_4. In Fig. 4 experimental values are polynomial expression of Eqq. (6) to (9) are plotted, together with the affinity law of Eq.1. It is evident that, for a pump working in inverse mode, modified affinity laws (*MAL*) behave much differently than affinity law.

Whenever the highest PAT efficiency η_B^{max} and the related speed N^{max} are known, the modified affinity laws improve the estimate of BEP values at rotational speed N differing from N^{max}.

By applying Suter parameters to the BEP line determined by *MAL* polynomials, an improvement in the estimated characteristic curves is expected. Values of σ^H and σ^η were calculated by the new approach and are showed in Fig. 4. Average values of σ^H and σ^η are equal to 0.0628 and 0.0366, respectively and significant improvement in the evaluation of the performances has been reached.

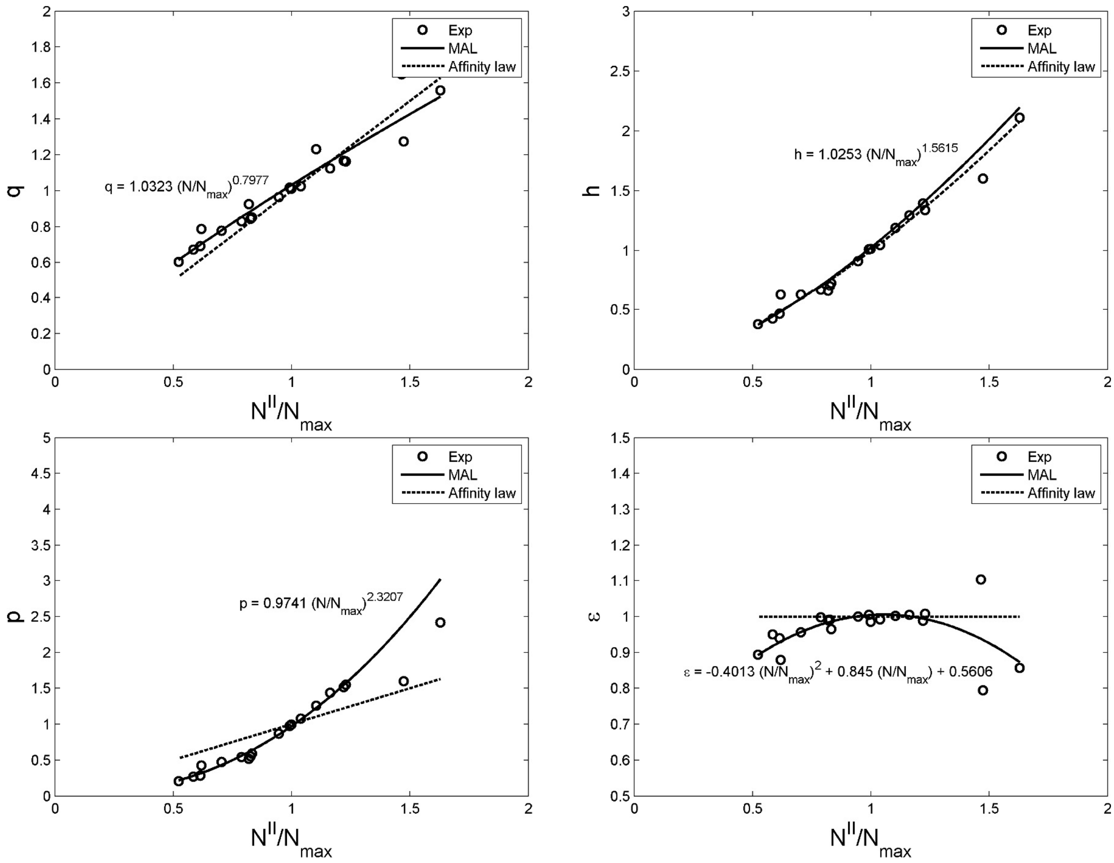

Fig. 3. MAL polynomials of Eq. 6 to 9.

5. Conclusion

In small hydro power plants, a PAT is usually used in a wide range of rotational speeds. In the design characteristic curves are determined on the basis of a single prototype curve by means of affinity law and Suter parameters. This approach produces some consistent error in the evaluation of the head drop when the rotational speed of the machine is far from the speed of the prototype.

In order to granting the satisfaction of the correct hydraulic constraint (pressure level within the network) and a correct calculation of produced energy a better estimate of performances curves is necessary. Based on a large set of test results for submersed semiaxial single stage pumps, a new method for the estimate of PAT working conditions is proposed. This method assume that the variation of BEP parameters with the rotational speed can be deduced by means of modified affinity laws (MAL).

By using MAL in conjunction with Suter parameters a reduction of the scatter between calculated and measured performances curves is observed. Therefore, a new design procedure based on MAL is now under development.

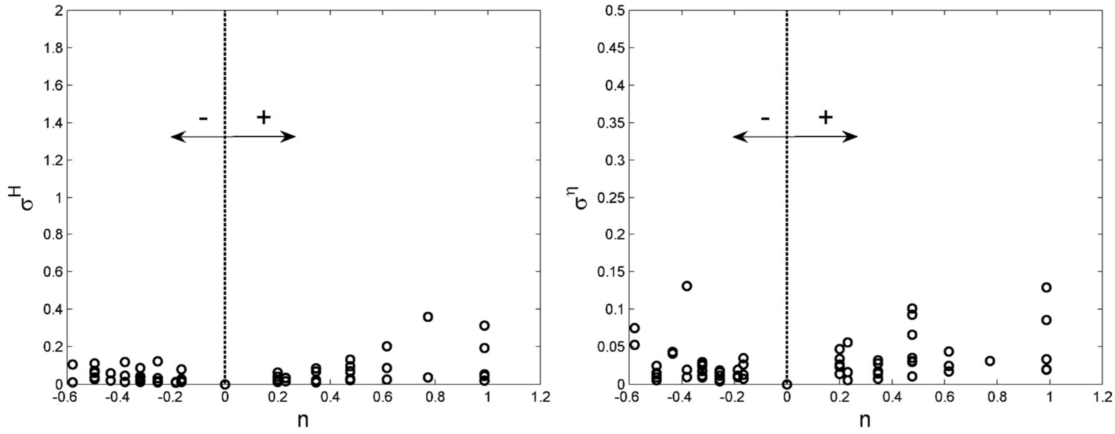

Fig. 4. MAL polynomials of Eq. 6 to 9.

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